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Thermal performance of extensive green roofs in a subtropical metropolitan area

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ABSTRACT

Extreme weather events caused by climate change intensify the heat island effect, and a lack of greenery in urban areas increases the psychological stress and anxiety of city dwellers. This study compared the temperature reductions and heat amplitude reductions provided by four types of green roofing that can cover bare rooftops. The four types of plants grown on extensive green roofs in this study were: shrubs, perennial herbs, vines, and groundcover; these are potentially healing plants. Furthermore, this study investigated the effects of air temperature, relative humidity, and solar radiation on temperature reduction of the rooftop. Four-stage field experiments under various ambient temperatures were conducted on the roof of a typical residential townhouse in the Taichung metropolitan area, in central Taiwan, which has a warm oceanic climate/humid subtropical climate (Cfa). The results indicated that the bottom temperature of the perennial herb, shrub, vine, and groundcover green roofs were lower than the bare rooftop temperature by 17.75 °C, 12.57 °C, 11.55 °C, and 9.31 °C, respectively. The heat amplitude reductions of the bare rooftop were defined as 1 minus the result of dividing the experimental temperature fluctuation by the rooftop temperature fluctuation; the heat amplitude reductions attributed to the shrub and perennial herb green roofs were similar (83.32% and 82.58%, respectively); smaller reductions were produced by the vine (79.78%) and groundcover (74.88%) roofs. Moreover, air temperature and solar radiation were positively related to temperature reduction of the bare rooftop, and relative humidity was negatively related to temperature reduction. Finally, plants in extensive green roofs can further reduce the surface temperature of a bare rooftop when compared with that of bare soil roofs.

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1. Introduction

Several studies have confirmed that nature exerts restorative effects: It restricts negative thoughts, elicits positive emotions, reduces arousal in bodily systems, reduces stress, and enhances direct attentiveness after stressful experiences due to working or studying [1–9]. Studies on nonpatient groups have revealed that significant psychophysiological restoration can be elicited through visual exposure to natural settings for 3–5 min at most or 20 s at least [5,10–13]. A green environment was reported to be associated with a greater restoration experience, in addition to conferring additional cognitive benefits lasting at least 30 min after leaving the environment [14]. Other studies have reported that building workers or occupants with a window view of nature or a view of indoor plants exhibit less stress, a superior health status, higher productivity, and lower blood pressure [15–18].

The term "healing" refers to a beneficial process that promotes overall well-being [19]. A "potentially healing plant" refers to a plant that has a relatively high healing potential compared with other plants. In urban settings, where most of the population has limited access to open space, parks, and greenery, rooftop space can be developed into visually pleasing and easily accessible healing places in the form of extensive green roofs to allow meditation, and rest. One of the essential design principles of a healing place is to provide natural elements, such as nontoxic plants with a greenish appearance, a pleasing fragrance, and flowers of distinct colors, not only for creating visual effects but also for attracting birds and insects such as butterflies [20]. A study demonstrated that trees, bushes, grass cover and flower beds can elicit a restorative

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experience, with grass cover exhibiting the highest effect, followed by trees, flower beds, and bushes [21]. By identifying features of pocket parks that may be related to health promotion, another study found that green groundcover and enclosed green niches are vital, whereas disturbing features (e.g., a playground and view outside park) should be avoided [22]. In the context of a private garden, natural elements were determined to result in a higher perceived restorativeness, compared with artificial elements [23]. Extensive green roofs are low-cost and lightweight systems that use substrates up to only 200 mm in thickness [24]. Previous studies on the thermal performance of extensive green roofs have frequently used drought-tolerant, low-maintenance plants, such as those of the *Sedum* or Crassulacean acid metabolism (CAM) plant [25], as experimental materials because of their ability to adapt in arid or semiarid environments. However, these plants have disadvantages including a lack of healing potential, such as a less greenish appearance, fewer or insignificant flowers, no pleasing fragrance, and a lower leaf area index – an index representing the planform area of leaf coverage [26]; a high leaf area index is extremely crucial for increasing shading effects and reducing rooftop surface temperature [27].

Although previous studies on the thermal performance of extensive green roofs have mainly emphasized their effectiveness in reducing the surface temperature of bare rooftops in specific climatic zones [24,27–31], information on the interactive relationships between the ambient environment and the temperature reduction of bare rooftops involving extensive green roofs is limited. For example, the effects of increasing air temperature and relative humidity on the temperature reduction of bare rooftops are not well known. In addition, whether higher solar radiation results in higher or lower temperature reduction of bare rooftops remains relatively unexplored.

Many studies have confirmed that extensive green roofs can effectively reduce surface temperature of bare rooftop, which in turn substantially reduces the cooling energy load and utility costs during hot summer days. Field measurements recorded by Jim and Peng [28] demonstrated that the extensive green rooftops of the Hong Kong railway station, which are covered by *Arachis pintoi* (perennial peanut), reduce the rooftop surface temperature by a maximum of 9 °C. Wong et al. [29] claimed that green roofs with high vegetation coverage tend to have lower surface temperature than the originally exposed rooftop surface. A maximum temperature difference of 18 °C was observed between bare rooftop and the bottom temperature of the extensive green roof in the multistory car park of a housing estate in Singapore during February and March. On the basis of field observations and measurements, Lin et al. [30] demonstrated that extensive green roofs reduced the rooftop surface temperature by up to 22.5 °C and 25.1 °C in Taipei (northern Taiwan) and Chiayi (southern Taiwan), respectively, during summer. Karachaliou, Santamouris, and Pangalou demonstrated that their green roof could lower the rooftop temperature of a conventional roof by 15 °C in Athens, Greece [32].

Extensive green roofs have many effects for combatting an increase in ambient temperature, including the shading, evapotranspiration, reflective, photosynthetic, and shielding effects of the plant layer as well as the insulation, absorption, and evaporation effects of the growth medium layer [26,33]. In addition to reducing energy consumption and providing a place for people's restorative experiences, extensive green roofs can exert cooling effects in urban environments [33], increase environmental comfort [34], provide ecological services [35], alleviate stormwater runoffs [36], and moderate city noise [37].

Taiwan consists of a large proportion of residential urban buildings with a significant cooling energy load during every summer. Extensive green roof systems can provide appreciable thermal and energy benefits. Therefore, the objectives of this study were to (1) compare the temperature reduction and heat amplitude reduction of a bare rooftop by adopting four types of extensive green roofs as well as a bare soil roof, and (2) investigate the effects of the ambient environment on the temperature reduction of the bare rooftop by using different extensive green roofs.

According to our review of the relevant literature, this study is the first to

(1) evaluate the temperature reduction of a bare rooftop by adopting four types of extensive green roofs consisting of potentially healing plants;
(2) investigate the heat amplitude reduction of a bare rooftop by using the same four types of extensive green roofs; and
(3) quantify the effects of air temperature, relative humidity, and solar radiation on magnitude of temperature reduction of the bare rooftop.

2. Study design

2.1. Experiment site

To investigate the temperature reduction and heat amplitude reduction of a bare rooftop by using the four extensive green roofs, field measurements were recorded on the rooftop of a common multistory residential town house (24°9′60″N, 120°40′56″E); such town houses constitute 54.21% of the buildings in the Taichung metropolitan area, the third largest city in Taiwan [38]. The site is located in a warm oceanic climate/humid subtropical climate (Cfa) zone, according to the East Asia map of the Köppen climate classification, with average temperature ranges of 23.0 °C–35.5 °C and 9.6 °C–29.0 °C and average relative humidity levels of 72.7% and 70.7% during summer and winter, respectively [39]. Fig. 1 shows the floor plans of the fourth and fifth floors. The experiment months, May and June, had a daytime temperature and average relative humidity of up to 38 °C and 76%, respectively (Table 1).

2.2. Description of plant materials

A total of four perennial and terrestrial species were selected in this study to reduce replanting costs (Fig. 2). Each species represented one plant type, namely groundcover, perennial herb, vine, and shrub. Trees were excluded because they typically require a growth medium layer that is at least 300 mm in thickness [26], and our growth medium layer was only 150 mm in thickness. *Cynodon L.C. Rich.* (Bermuda grass) was selected as groundcover because it is fast growing, tough, trampling resistant, drought tolerant, and heat tolerant, and can easily achieve 100% coverage. Furthermore, it provides an excellent environment for evening active workouts, a year-round soothing lush view for passive gazing, or simply a place to relax or meditate.

The perennial herb *Impatiens walleriana* (impatiens, busy Lizzy) was chosen because it flowers profusely year-round in more than 40 different colors, e.g. orange, white, pink, purple, and red. It grows vigorously, can be easily managed, and can easily achieve 100% coverage. The seedpod explodes on ripening, thus reducing replanting costs. *Impatiens walleriana* provides a year-round visually pleasing environment and a pleasant setting for interacting with insects such as butterflies.

Wisteria sinensis (wisteria) was selected because it is a perennial climbing vine with an attractive violet, blue, and white raceme; the flowers produce a distinctive fragrance and bloom in April and May. It is sunlight, heat, and cold tolerant; fast growing; and easy to manage, and has a long lifespan (more than 100 years). *Wisteria sinensis* provides a visually and olfactorily pleasing environment and a pleasant setting for interacting with insects.

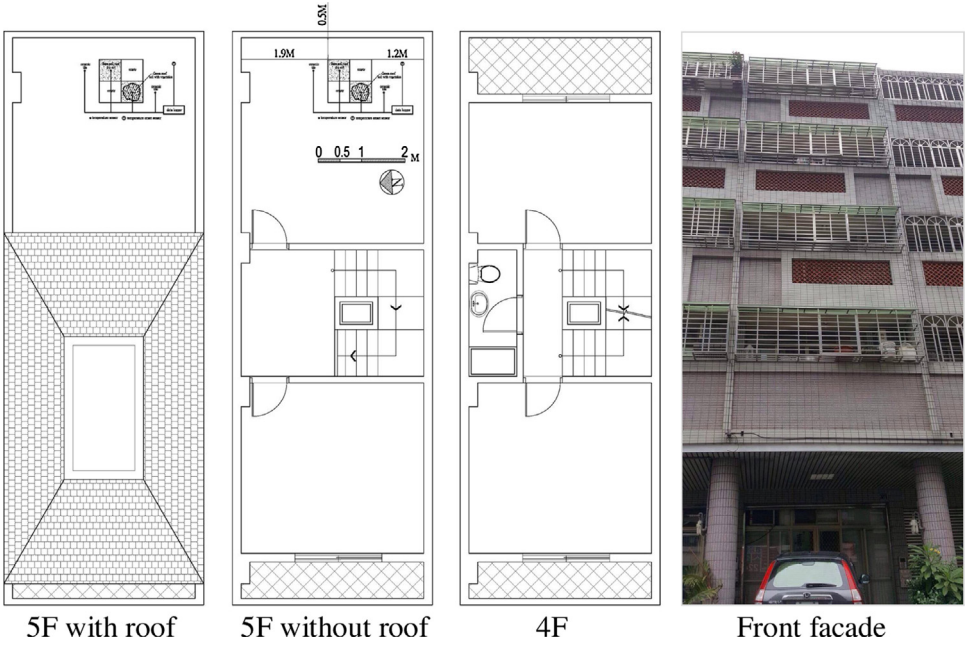

Fig. 1. Floor plans of the fourth (middle right) and fifth floors (left and middle left). Four blocks on the fifth floor served as experimental blocks (left and middle left). Front façade of the experimental building (right). (The North District of the Taichung metropolitan area, Taiwan, served as the experimental site).

Table 1
Weather data for the experiment site in Taichung, Taiwan (2013/5/20 06:00 ~ 2013/6/27 18:00).

Stage	First stage *Aglaia odorata Lour.*	Second stage *Impatiens walleriana*	Third stage *Wisteria sinensis*	Fourth stage *Cynodon L.C. Rich.*
Period of measurement	2013/5/20 ~ 5/26	2013/5/28 ~ 6/03	2013/6/09 ~ 6/15	2013/6/21 ~ 6/27
Range of air temperature (°C)	23.81 ~ 35.34	27.09 ~ 37.78	25.99 ~ 36.50	25.19 ~ 37.62
Mean air temperature (°C)	29.15	33.24	30.43	32.14
Range of rooftop temperature (°C)	25.13 ~ 43.84	28.66 ~ 51.86	27.47 ~ 45.45	28.66 ~ 44.46
Mean rooftop temperature (°C)	31.13	37.96	32.53	34.51
Maximum solar radiation (W/m^2)	940.6	1000.6	983.1	1015.6
Mean relative humidity (%)	75.97	59.45	74.16	65.00
Date selected for further analysis	2013/5/25–5/26	2013/5/31–6/01	2013/6/12–6/13	2013/6/23–6/24

Fig. 2. Four plant materials include *Aglaia odorata Lour.* (top left), *Impatiens walleriana* (top right), *Wisteria sinensis* (bottom left), *Cynodon L.C. Rich.* (bottom right).

The shrub *Aglaia odorata Lour.* (orchid tree) was chosen because it is evergreen, fast growing, easy to manage, suitable for various soils, and air pollution resistant. It has very dense and multilayered leaves that exert shading effects. In addition, *Aglaia odorata Lour.* produces red berries as fruit, which attract birds. An extremely fragrant yellow flower blooms from July to November and provides a visually and olfactorily pleasing environment and a pleasant setting for interacting with birds and insects.

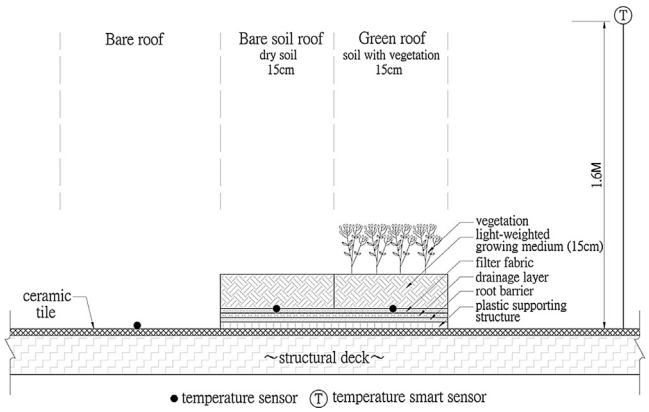

Fig. 3. Cross section of the experiment setup.

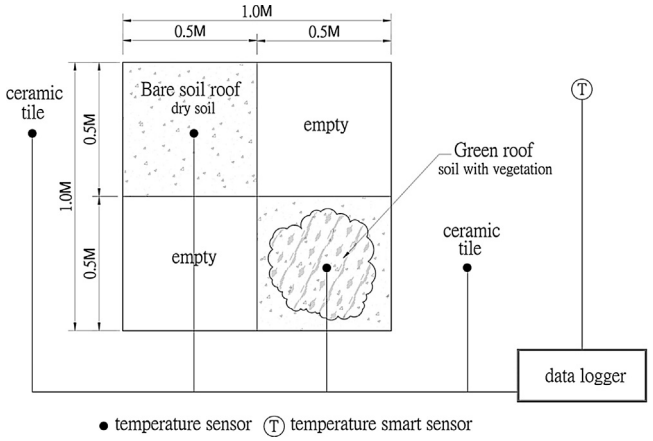

Fig. 4. Plan of the experiment setup.

2.3. Experimental design

A planting bed was constructed using glass bricks in April 2013. This planting bed was divided into four smaller planting beds ($50 \times 50 \times 19$ cm) by using two 6-mm-thick acrylic panels [40]. To prevent plant root penetration into the structural deck, increase ventilation, and facilitate water drainage, the extensive green roof was set up by stacking several layers of materials in the following order from bottom to top: plastic supporting structure, root barrier, drainage layer, filter fabric, lightweight growth medium, and vegetation (Fig. 3). Two diagonally aligned beds were left empty. Of the other two diagonally aligned beds, one was considered the control bed and another the experimental bed (Fig. 4). The control bed was filled with a bare, lightweight, 150-mm-thick growth medium, and was referred to as the bare soil roof; the experimental bed was filled with the same type of lightweight, 150-mm-thick growth medium and one of the four types of plants, and this is referred to as the green roof. Finally, a transparent plastic sheet was placed 150 cm above the planting beds to prevent temperature interference due to minor precipitation during the experiment period (Fig. 2, bottom left).

The lightweight growth medium (peaty soil/vermiculite/perlite/sandy loam soil, 1:1:1:1) [41] was used to alleviate the weight load on the building. This medium supported the growth of various plant types. Four experimental plants were individually investigated in four stages in the following order: *Aglaia odorata Lour.*, *Impatiens walleriana, Wisteria sinensis, and Cynodon L.C. Rich.*

All four plants were planted with 100% coverage to achieve the optimal effects of temperature reduction and heat amplitude reduction, compared with bare rooftop. The bare soil roofs and the green roofs were exposed to direct sunlight approximately between 10:00 and 12:30 during the experiment period from May 20, 2013, to June 27, 2013. The shadow interference did not affect the measurements recorded around noon, when the green roof reached its highest thermal performance.

2.4. Instrument settings and measurement data

Measuring points were positioned at the bottom center of the bare soil and green roofs, and two corresponding measuring points of the bare rooftop were located near the sides–in close contact with the surface of the roof's ceramic tile. Relative humidity (12-bit Temperature/Relative Humidity Smart Sensor, S-THB-M002), air temperature (12-bit Temperature/Relative Humidity Smart Sensor, S-THB-M002), and solar radiation (Solar Radiation Smart Sensor, S-LIB-M003) were measured at 160 cm above the rooftop [28,29] to prevent any reflective interference from the rooftop or wall surfaces from this and adjacent buildings. A thermal monitoring system including three weather data loggers (HOBO Micro Station Data Logger) was used to obtain all measurements every 10 min. The experiment was conducted in four stages: first, May 20–26, 2013 (*Aglaia odorata Lour.*); second, May 28–June 3, 2013 (*Impatiens wal-*

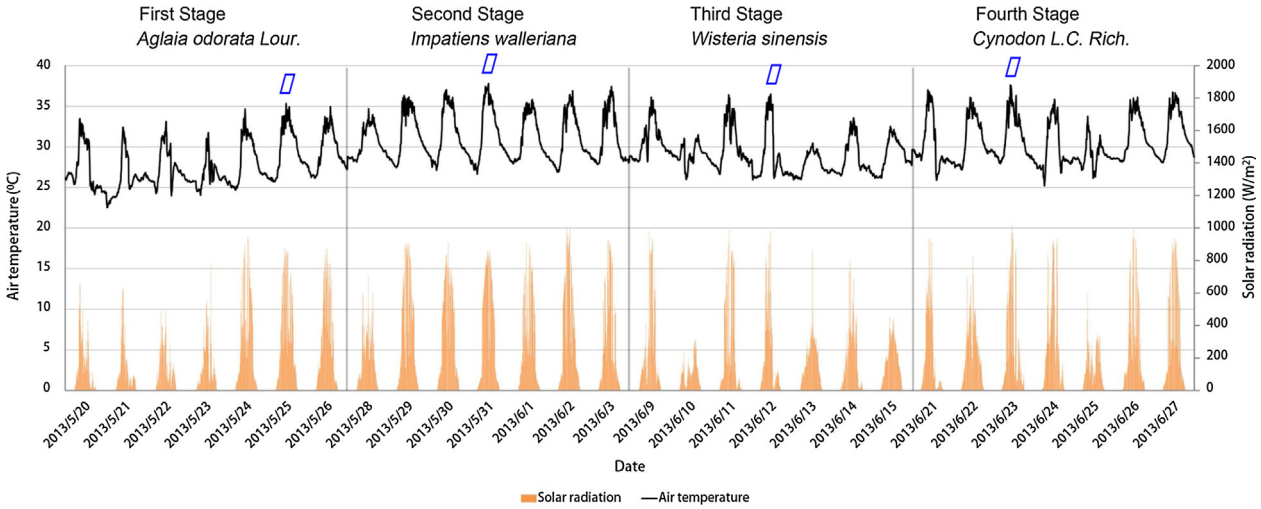

Fig. 5. Air temperature and solar radiation measurements (2013/05/20 ~ 2013/06/27). Four days selected for further analysis, highlighted with check marks, are May 25 to 26, 2011, May 31 to June 1, 2011, June 12 to 13, 2011, and June 23 to 24, 2011.

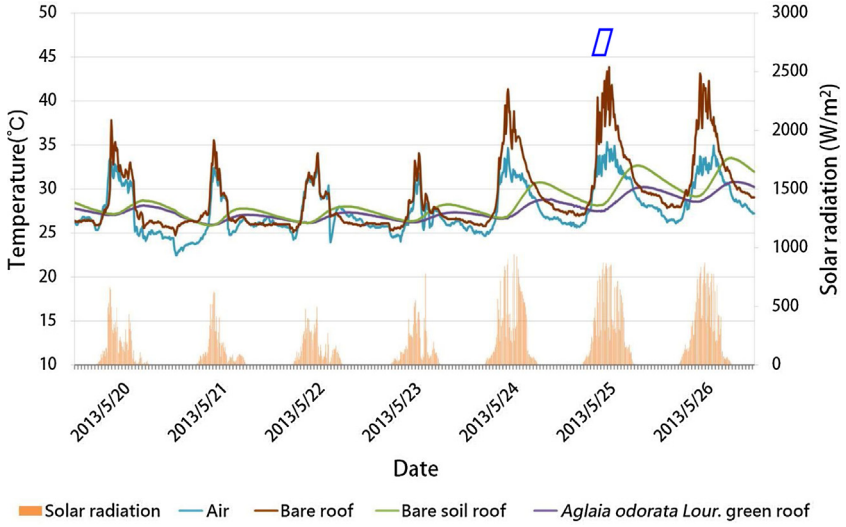

Fig. 6. Temperatures and solar radiation of the *Aglaia odorata Lour.* green roof (2013/5/20 ~ 2013/5/26). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

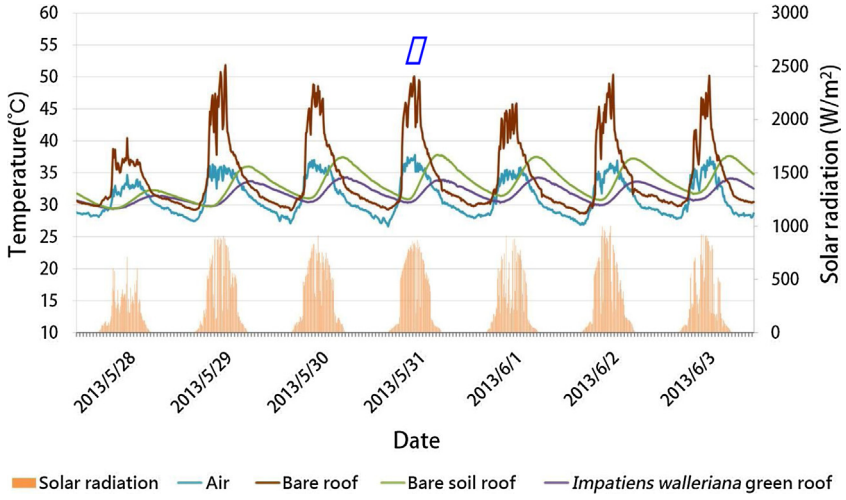

Fig. 7. Temperatures and solar radiation of the *Impatiens walleriana* green roof (2013/5/28 ~ 2013/6/03). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

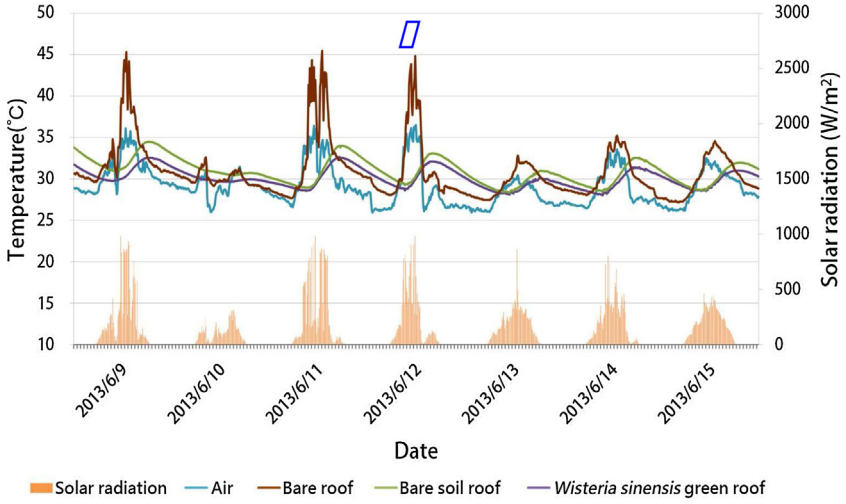

Fig. 8. Temperatures and solar radiation of the *Wisteria sinensis* green roof (2013/6/09 ~ 2013/6/15). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

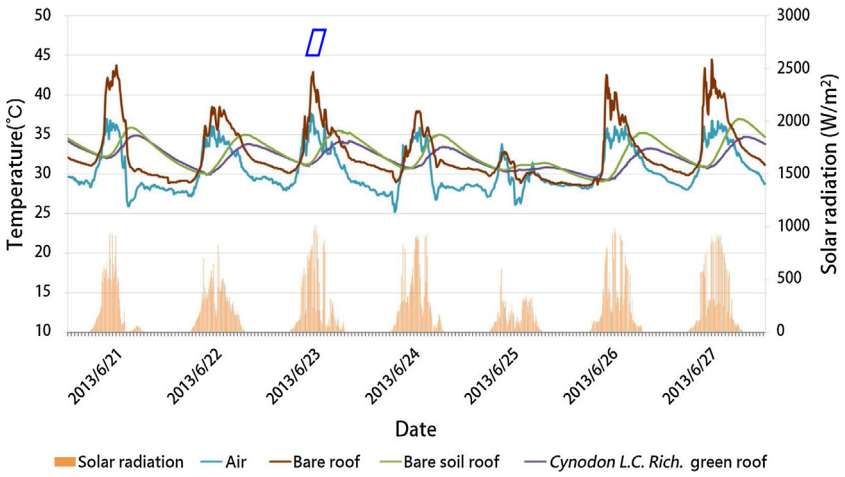

Fig. 9. Temperatures and solar radiation of the *Cynodon L.C. Rich.* green roof (2013/6/21 ~ 2013/6/27). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Heat amplitude reduction of the extensive green roofs with and without *Aglaia odorata Lour.* (2013/5/25 06:00 ~ 2013/5/26 06:00).

Position of the thermocouple		Average temperature (°C)	Range of temperature (°C)	Difference in temperature (°C)	Heat amplitude reduction
Air temperature		29.57	26.11 ~ 35.34	9.23	-
On the surface of bare roof		32.04	27.17 ~ 43.84	16.67	-
At the bottom	Bare soil	30.53	28.12 ~ 32.67	4.55	72.71%
	Aglaia odorata Lour.	29.05	27.46 ~ 30.24	2.78	83.32%

Note: "Heat amplitude reduction" is equal to "1 minus the result of dividing the experimental temperature fluctuation by the rooftop temperature fluctuation."

Table 3
Bottom temperature and temperature reduction of the extensive green roofs with and without *Aglaia odorata Lour.* (2013/5/25 06:00 ~ 2013/5/25 18:00).

Position of the thermocouple		06:00–07:00 (°C)	07:00–08:00 (°C)	08:00–09:00 (°C)	09:00–10:00 (°C)	10:00–11:00 (°C)	11:00–12:00 (°C)	12:00–13:00 (°C)	13:00–14:00 (°C)	14:00–15:00 (°C)	15:00~16:00 (°C)	16:00~17:00 (°C)	17:00~18:00 (°C)
Air temperature		26.82	28.09	31.05	32.53	32.93	33.82	33.81	33.57	32.44	31.82	31.34	30.95
On the surface of bare roof		27.73	29.09	31.21	37.24	39.26	40.28	40.53	38.05	36.17	34.31	33.47	32.59
At the bottom	Bare soil	28.47	28.28	28.17	28.15	28.23	28.56	29.14	29.84	30.60	31.35	31.98	32.41
	Aglaia odorata Lour.	27.74	27.59	27.51	27.50	27.51	27.71	28.06	28.44	28.80	29.20	29.56	29.86
Temperature reduction	Bare soil	−0.74	0.81	3.04	9.09	11.03	11.72	11.39	8.21	5.57	2.96	1.49	0.18
	Aglaia odorata Lour.	−0.01	1.50	3.70	9.74	11.75	12.57	12.47	9.61	7.37	5.11	3.91	2.73

leriana); third, June 9–15, 2013 (*Wisteria sinensis*); and fourth, June 21–27, 2013 (*Cynodon L.C. Rich.*). Each plant was used for seven consecutive days.

Due to equipment limitations, we could not conduct simultaneous experiments for the four planting beds and one control bed. Instead, we set up a four-stage experiment, with each stage involving one experimental bed and one control bed, to obtain the comparison of the temperature reduction and heat amplitude reduction of the bare rooftop between the bare soil roof and the green roofs, individually. Furthermore, by computing the relative measures on temperature reduction of the bare rooftop in Table 10, we could compare the temperature reduction efficiency of the bare rooftop across the four types of green roofs.

3. Results and discussion

3.1. Air temperature, relative humidity, and solar radiation

Table 1 presents the means and ranges of air temperature and rooftop temperature, the maximum solar radiation, and the mean relative humidity. The daily air temperature and solar radiation throughout the experiment period are shown in Fig. 5. The mean air temperatures for the first, second, third, and fourth stages were 29.15 °C, 33.24 °C, 30.43 °C, and 32.14 °C, respectively, and the mean rooftop temperatures were 31.13 °C, 37.96 °C, 32.53 °C, and 34.5 °C, respectively. The mean relative humidity for the four stages was 75.97%, 59.45%, 74.16%, and 65.00%, respectively.

For each stage, one full day, from 06:00 to 06:00 of the next day, was selected for further analysis because sunrise occurred at approximately 05:10 during May and June in 2013 [39]. The four days were selected on the basis of the following criteria: high temperature at noon, a relatively stable air temperature progression during 24 h, and ample solar radiation with relatively low cloud interference. The following days represented the first, second, third, and fourth stages, respectively: May 25 (06:00 am) to May 26 (06:00 am; Fig. 6); May 31 (06:00 am) to June 1 (06:00 am; Fig. 7); June 12 (06:00 am) to June 13 (06:00 am; Fig. 8); and June 23 (06:00 am) to June 24 (06:00 am; Fig. 9). In addition, temperature reduction and heat amplitude reduction of bare rooftops were calculated for these 4 days.

3.2. Thermal performance of the extensive green roof with and without Aglaia odorata Lour

The first stage involved investigating the temperature reduction and heat amplitude reduction of bare rooftop by the *Aglaia odorata Lour.* green roof. Because of the evapotranspiration, shading, shielding, photosynthetic, and reflective effects of the vegetation layer as well as the insulation, absorption, and evaporation effects of the growth medium layer, the *Aglaia odorata Lour.* green roof significantly reduced the heat flux on May 25 [26,33]. When the

Table 4
Heat amplitude reduction of the extensive green roofs with and without *Impatiens walleriana*. (2013/5/31 06:00 ~ 2013/6/01 06:00).

Position of the thermocouple		Average temperature (°C)	Range of temperature (°C)	Difference in temperature (°C)	Heat amplitude reduction
Air temperature		31.52	27.92 ~ 37.78	9.86	-
On the surface of bare roof		35.03	29.55 ~ 50.04	20.49	-
At the bottom	Bare soil	34.16	30.87 ~ 37.81	6.94	66.13%
	Impatiens walleriana	32.09	30.34 ~ 33.91	3.57	82.58%

Note: "Heat amplitude reduction" is equal to "1 minus the result of dividing the experimental temperature fluctuation by the rooftop temperature fluctuation."

Table 5
Bottom temperature and temperature reduction of the extensive green roofs with and without *Impatiens walleriana* (2013/5/31 06:00 ~ 2013/5/31 18:00).

Position of the thermocouple		06:00–07:00 (°C)	07:00–08:00 (°C)	08:00–09:00 (°C)	09:00–10:00 (°C)	10:00–11:00 (°C)	11:00–12:00 (°C)	12:00–13:00 (°C)	13:00–14:00 (°C)	14:00–15:00 (°C)	15:00–16:00 (°C)	16:00–17:00 (°C)	17:00–18:00 (°C)
Air temperature		28.48	30.05	33.90	36.00	36.97	37.25	35.57	35.78	35.03	34.04	32.67	32.13
On the surface of bare roof		29.75	30.31	34.50	44.55	46.28	48.33	45.57	43.16	39.28	37.44	35.67	34.53
At the bottom	Bare soil	31.87	31.56	31.25	30.95	30.93	31.49	32.65	34.01	35.32	36.51	37.37	37.76
	Impatiens walleriana	31.06	30.81	30.59	30.41	30.39	30.58	31.05	31.73	32.45	33.09	33.57	33.78
Temperature reduction	Bare soil	−2.12	−1.25	3.25	13.60	15.35	16.84	12.92	9.15	3.96	0.93	−1.70	−3.23
	Impatiens walleriana	−1.31	−0.50	3.91	14.14	15.89	17.75	14.52	11.43	6.83	4.35	2.10	0.75

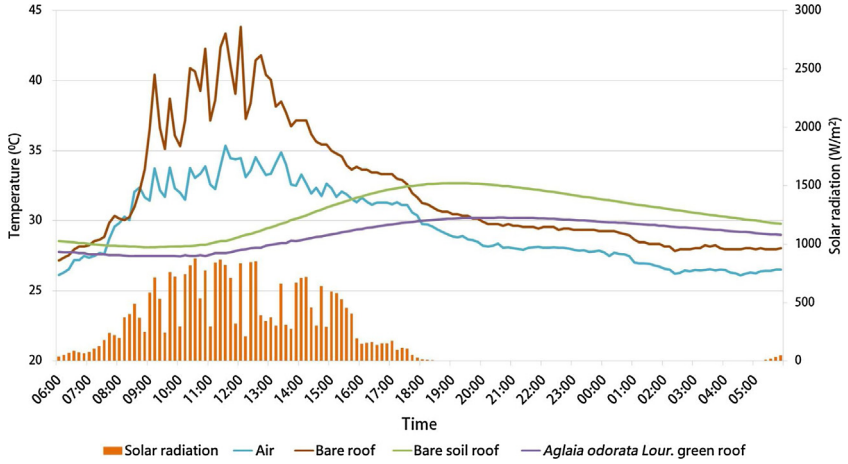

Fig. 10. Solar radiation and the bottom temperature of the extensive green roofs with and without *Aglaia odorata Lour.* (2013/5/25 06:00 ~ 2013/5/26 06:00). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

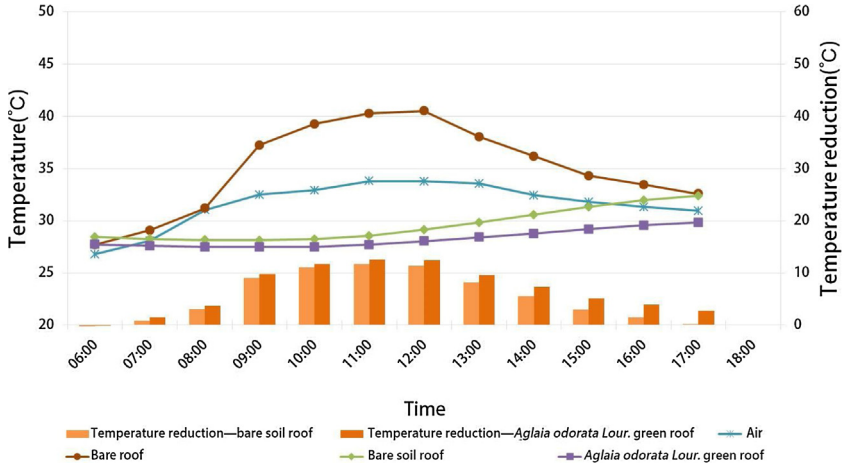

Fig. 11. Temperature and temperature reduction of the extensive green roofs with and without *Aglaia odorata Lour.* (2013/5/25 06:00 ~ 2013/5/25 18:00). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

average air temperature and rooftop temperature were 29.57 °C and 32.04 °C, respectively, the average bottom temperature of the *Aglaia odorata Lour.* green roof was only 29.05 °C (Table 2; Fig. 10). The greatest temperature reduction (12.57 °C), as measured by the temperature difference between the bottom temperature of the *Aglaia odorata Lour.* green roof and the temperature of the bare rooftop, occurred during the 11:00–12:00 time slot (Table 3; Fig. 11). The aforementioned findings demonstrate that the *Aglaia odorata Lour.* green roof caused average and maximum temperature reductions of 2.99 °C (32.04 °C–29.05 °C) and 12.57 °C (40.28 °C–

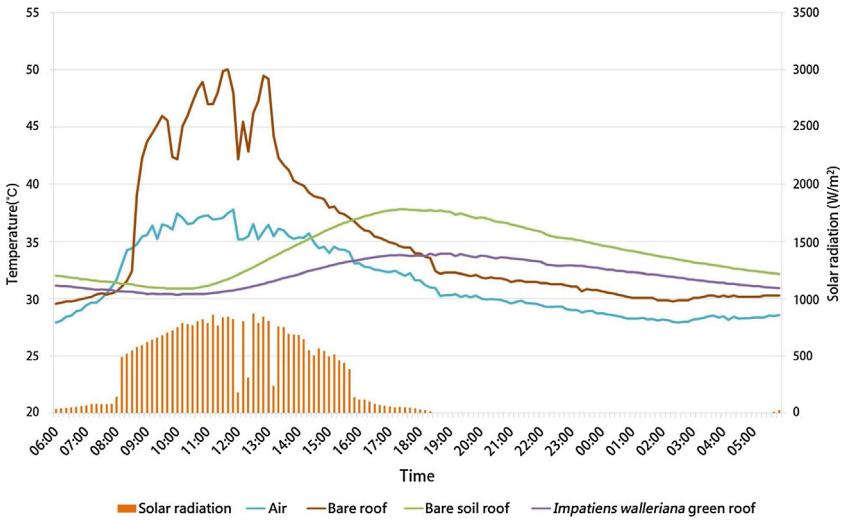

Fig. 12. Solar radiation and the bottom temperature of the extensive green roofs with and without *Impatiens walleriana* (2013/5/31 06:00 ~ 2013/6/01 06:00). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

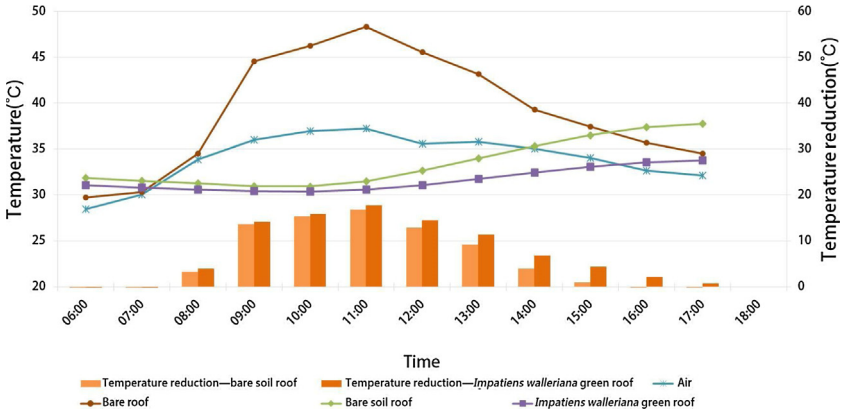

Fig. 13. Temperature and temperature reduction of the extensive green roofs with and without *Impatiens walleriana* (2013/5/31 06:00 ~ 2013/5/31 18:00). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

27.71 °C), respectively, on May 25 (06:00–18:00). Compared with the bare soil roof, the *Aglaia odorata Lour.* green roof provided a maximum additional rooftop temperature reduction of 2.55 °C (2.73 °C–0.18 °C) on May 25, 17:00–18:00 (Table 3; Fig. 11).

Furthermore, the *Aglaia odorata Lour.* green roof contributed in stabilizing the rooftop temperature, which consequently reduced indoor temperature fluctuation, increased the comfort level, and reduced the cooling energy load, particularly on the top floor [40]. On May 25 (06:00–18:00), the *Aglaia odorata Lour.* green roof significantly reduced the heat amplitude of the bare rooftop by 83.32% (Table 2; Fig. 10). The heat amplitude reduction was calculated as 1 minus the result of dividing the experimental temperature fluctuation by the rooftop temperature fluctuation. Compared with the bare soil roof, the *Aglaia odorata Lour.* green roof provided an additional 10.61% reduction in the heat amplitude of bare rooftop.

3.3. *Thermal performance of the extensive green roof with and without* Impatiens walleriana

The second stage involved investigating the temperature reduction and heat amplitude reduction of bare rooftop by the *Impatiens walleriana* green roof. Because of the aforementioned effects of the vegetation layer and the growth medium layers, the *Impatiens walleriana* green roof significantly reduced the heat flux on May 31 [26,33]. When the average air temperature and rooftop temperature were 31.52 °C and 35.03 °C, respectively, the average bottom temperature of the *Impatiens walleriana* green roof was only 32.09 °C (Table 4; Fig. 12). The greatest temperature reduction was 17.75 °C during the 11:00–12:00 time slot, as measured by the temperature difference between the bottom temperature of the *Impatiens walleriana* green roof and the temperature of the bare rooftop (Table 5; Fig. 13). The aforementioned findings demonstrate that the *Impatiens walleriana* green roof caused an average and maximum reduction of 2.94 °C (35.03 °C–32.09 °C) and 17.75 °C (48.33 °C–30.58 °C), respectively, on May 31 (06:00–18:00). Compared with the bare soil roof, the *Impatiens walleriana* green roof provided a maximum additional rooftop temperature reduction of 3.98 °C (-3.23 °C–0.75 °C) on May 31, 17:00–18:00 (Table 5; Fig. 13).

Furthermore, the *Impatiens walleriana* green roof contributed in stabilizing the rooftop temperature. On May 31 (06:00–18:00), the *Impatiens walleriana* green roof significantly reduced the heat amplitude of the bare rooftop by 82.58% (Table 4; Fig. 12); this reduction was only slightly smaller than that caused by the *Aglaia odorata Lour.* green roof. Compared with the bare soil roof, the *Impatiens walleriana* green roof provided an additional 16.45% reduction in the heat amplitude of the bare rooftop.

Table 6
Heat amplitude reduction of the extensive green roofs with and without *Wisteria sinensis*. (2013/6/12 06:00 ~ 2013/6/13 06:00).

Position of the thermocouple		Average temperature (°C)	Range of temperature (°C)	Difference in temperature (°C)	Heat amplitude reduction
Air temperature		28.60	25.94 ~ 36.50	10.56	-
On the surface of bare roof		33.22	27.47 ~ 44.83	17.36	-
At the bottom	Bare soil	30.92	29.02 ~ 33.08	4.06	76.61%
	Wisteria sinensis	30.27	28.59 ~ 32.10	3.51	79.78%

Note: "Heat amplitude reduction" is equal to "1 minus the result of dividing the experimental temperature fluctuation by the rooftop temperature fluctuation."

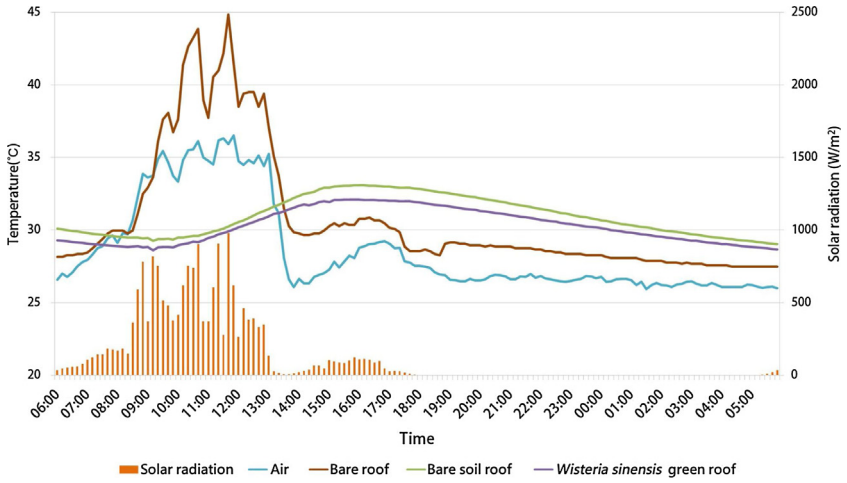

Fig. 14. Solar radiation and the bottom temperature of the extensive green roofs with and without *Wisteria sinensis* (2013/6/12 06:00 ~ 2013/6/13 06:00). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4. Thermal performance of the extensive green roof with and without Wisteria sinensis

The third stage involved investigating the temperature reduction and heat amplitude reduction of bare rooftop by the *Wisteria sinensis* green roof. Because of the aforementioned effects of the vegetation layer and growth medium layers, the *Wisteria sinensis* green roof significantly reduced the heat flux on June 12 [26,33]. When the average air temperature and rooftop temperature were 28.60 °C and 33.22 °C, respectively, the average bottom temperature of the *Wisteria sinensis* green roof was only 30.27 °C (Table 6; Fig. 14). The greatest temperature reduction was 12.15 °C during the 10:00–11:00 time slot, as measured by the temperature difference between the bottom temperature of the *Wisteria sinensis* green roof and the temperature of the bare rooftop (Table 7; Fig. 15). The aforementioned findings demonstrate that the *Wisteria sinensis* green roof caused an average and maximum reductions of 2.95 °C (33.22 °C–30.27 °C) and 12.15 °C (41.27 °C–29.12 °C), respectively, on June 12 (06:00–18:00). Compared with the bare soil roof, the *Wisteria sinensis* green roof provided a maximum additional rooftop temperature reduction of 0.63 °C (1.69 °C–1.06 °C) on June 12, 08:00–09:00 (Table 7; Fig. 15).

Furthermore, the *Wisteria sinensis* green roof contributed in stabilizing the rooftop temperature. On June 12 (06:00–18:00), the *Wisteria sinensis* green roof significantly reduced the heat amplitude of the bare rooftop by 79.78% (Table 6; Fig. 14). Compared with the bare soil roof, the *Wisteria sinensis* green roof provided an additional 3.17% reduction in the heat amplitude of the bare rooftop.

3.5. Thermal performance of the extensive green roof with and without Cynodon L.C.Rich.

The fourth stage involved investigating the temperature reduction and heat amplitude reduction of bare rooftop by the *Cynodon L.C. Rich.* green roof. Because of the aforementioned effects of the vegetation layer and the growth medium layers, the *Cynodon L.C. Rich.* green roof significantly reduced the heat flux on June 23 [26,33]. When the average air temperature and rooftop temperature were 30.48 °C and 35.63 °C, respectively, the average bottom temperature of the *Cynodon L.C. Rich.* green roof was only 32.68 °C (Table 8; Fig. 16). The greatest temperature reduction was 9.31 °C during the 11:00–12:00 time slot, as measured by the temperature difference between the bottom temperature of the *Cynodon L.C. Rich.* green roof and the temperature of the bare rooftop (Table 9; Fig. 17). The aforementioned findings demonstrated that the *Cynodon L.C. Rich.* green roof caused an average and maximum reduction of 2.95 °C (35.63 °C–32.68 °C) and 9.31 °C (40.83 °C–31.52 °C), respectively, on June 23 (06:00–18:00). Compared with the bare soil roof, the *Cynodon L.C. Rich.* green roof provided a maximum additional rooftop temperature reduction of 1.57 °C (1.97 °C–0.40 °C) on June 23, 15:00–16:00 (Table 9; Fig. 17).

Furthermore, the *Cynodon L.C. Rich.* green roof contributed in stabilizing the rooftop temperature. On June 23 (06:00–18:00), the *Cynodon L.C. Rich.* green roof significantly reduced the heat amplitude of the bare rooftop by 74.88% (Table 8; Fig. 16). Compared with the bare soil roof, the *Cynodon L.C. Rich.* green roof provided an additional 9.35% reduction in the heat amplitude of the bare rooftop.

3.6. Comparison of thermal performance between four extensive green roofs

Because of the reflective, photosynthetic, shielding, shading, and evapotranspiration effects of the vegetation layer and the effects of insulation, absorption, and evaporation of the growth medium layer, the perennial herb green roof showed the largest magnitude of temperature reduction of the bare rooftop (*Impatiens walleriana*; maximum temperature reduction of the bare rooftop, 17.75 °C; maximum temperature reduction divided by the highest air tem-

Table 7
Bottom temperature and temperature reduction of the extensive green roofs with and without *Wisteria sinensis* (2013/6/12 06:00 ~ 2013/6/12 18:00).

Position of the thermocouple		06:00–07:00 (°C)	07:00–08:00 (°C)	08:00–09:00 (°C)	09:00–10:00 (°C)	10:00–11:00 (°C)	11:00–12:00 (°C)	12:00–13:00 (°C)	13:00–14:00 (°C)	14:00–15:00 (°C)	15:00–16:00 (°C)	16:00–17:00 (°C)	17:00–18:00 (°C)
Air temperature		27.12	28.82	30.91	34.35	35.05	35.57	34.70	29.82	26.67	27.78	29.02	28.28
On the surface of bare roof		28.26	29.22	30.55	35.83	41.27	41.28	39.13	32.92	29.75	30.36	30.69	29.34
At the bottom	Bare soil	29.97	29.69	29.49	29.36	29.56	30.07	30.92	31.83	32.62	33.02	33.05	32.92
	Wisteria sinensis	29.19	28.99	28.86	28.77	29.12	29.73	30.49	31.24	31.08	32.06	32.07	31.97
Temperature reduction	Bare soil	−1.71	−0.47	1.06	6.47	11.71	11.21	8.21	1.09	−2.87	−2.66	−2.36	−3.58
	Wisteria sinensis	−0.93	0.23	1.69	7.06	12.15	11.55	8.64	1.68	−1.33	−1.70	−1.38	−2.63

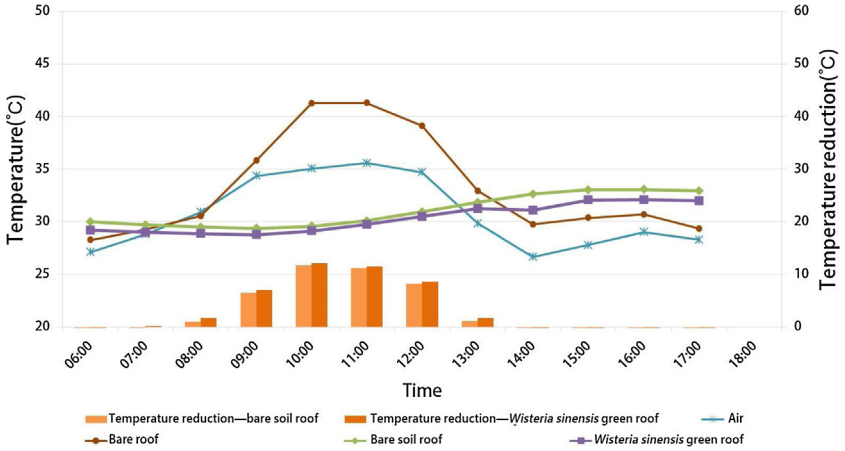

Fig. 15. Temperature and temperature reduction of the extensive green roofs with and without *Wisteria sinensis* (2013/6/12 06:00 ~ 2013/6/12 18:00). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 8
Heat amplitude reduction of the extensive green roofs with and without *Cynodon L.C. Rich.* (2013/6/23 06:00 ~ 2013/6/24 06:00).

Position of the thermocouple		Average temperature (°C)	Range of temperature (°C)	Difference in temperature (°C)	Heat amplitude reduction
Air temperature		30.48	27.16 ~ 37.62	10.46	-
On the surface of bare roof		35.63	30.26 ~ 42.88	12.62	-
At the bottom	Bare soil	33.31	31.13 ~ 35.48	4.35	65.53%
	Cynodon L.C. Rich.	32.68	30.98 ~ 34.15	3.17	74.88%

Note: "Heat amplitude reduction" is equal to "1 minus the result of dividing the experimental temperature fluctuation by the rooftop temperature fluctuation."

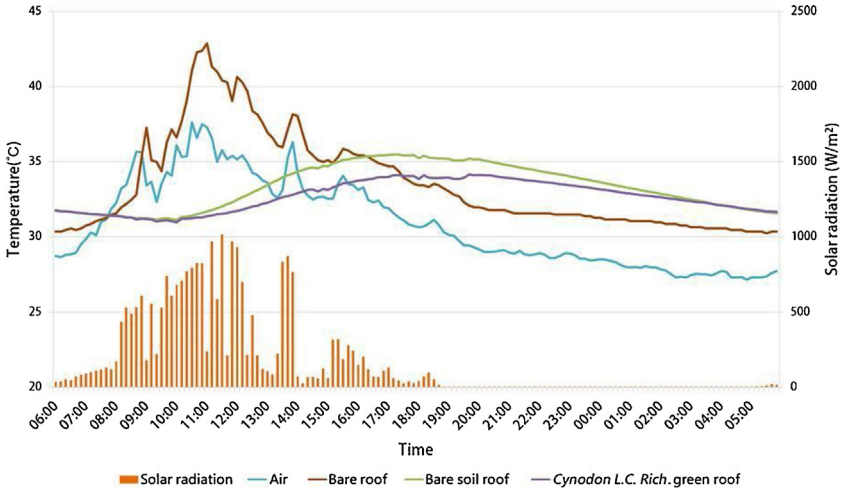

Fig. 16. Solar radiation and the bottom temperature of the extensive green roofs with and without *Cynodon L.C. Rich.* 2013/6/23 06:00 ~ 2013/6/24 06:00). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 9
Bottom temperature and temperature reduction of the extensive green roofs with and without *Cynodon L.C. Rich.* (2013/6/23 06:00 ~ 2013/6/23 18:00).

Position of the thermocouple		06:00–07:00 (°C)	07:00–08:00 (°C)	08:00–09:00 (°C)	09:00–10:00 (°C)	10:00–11:00 (°C)	11:00–12:00 (°C)	12:00–13:00 (°C)	13:00–14:00 (°C)	14:00–15:00 (°C)	15:00–16:00 (°C)	16:00–17:00 (°C)	17:00–18:00 (°C)
Air temperature		28.92	30.72	34.13	33.56	36.41	35.86	34.61	33.97	32.99	33.28	32.60	31.25
On the surface of bare roof		30.46	31.10	32.73	35.87	39.86	40.83	39.14	36.82	36.03	35.42	35.17	34.16
At the bottom	Bare soil	31.68	31.47	31.31	31.20	31.39	31.98	32.88	33.86	34.55	35.02	35.36	35.45
	Cynodon L.C. Rich.	31.67	31.49	31.29	31.10	31.21	31.52	31.96	32.57	33.07	33.45	33.87	34.05
Temperature reduction	Bare soil	−1.22	−0.37	1.42	4.67	8.47	8.85	6.26	2.96	1.48	0.40	−0.19	−1.29
	Cynodon L.C. Rich.	−1.21	−0.39	1.44	4.77	8.65	9.31	7.18	4.25	2.96	1.97	1.30	0.11

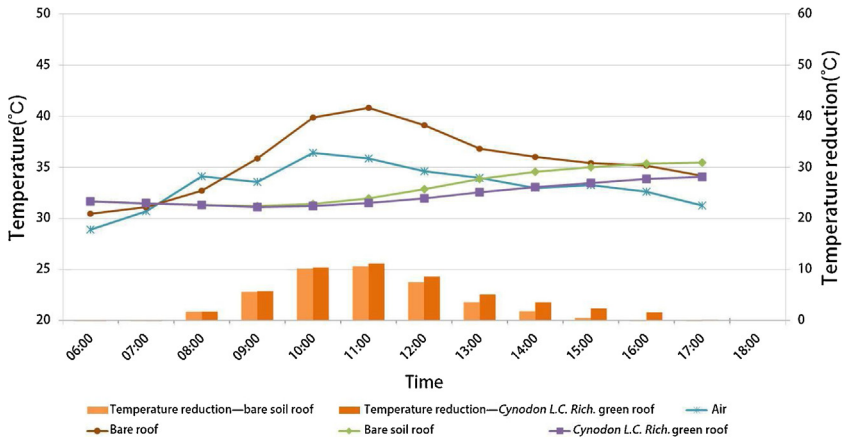

Fig. 17. Temperature and temperature reduction of the extensive green roofs with and without *Cynodon L.C. Rich.* 2013/6/23 06:00 ~ 2013/6/23 18:00). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 10
Proportion of maximum temperature reduction in the highest air temperature or rooftop temperature and heat amplitude reduction caused by four types of green roofs.

Stage	First stage	Second stage	Third stage	Fourth stage
Type of green roof	Shrub *Aglaia odorata Lour.*	Perennial herb *Impatiens walleriana*	Vine *Wisteria sinensis*	Groundcover *Cynodon L.C. Rich.*
Highest air temperature (A)	33.82 °C	37.25 °C	35.57 °C	35.86 °C
Highest rooftop temperature (C)	40.28 °C	48.33 °C	41.28 °C	40.83 °C
Maximum temperature reduction (B)	12.57 °C	17.75 °C	11.55 °C	9.31 °C
Maximum temperature reduction divided by the highest air temperature (B/A)	37.17%	47.65%	32.47%	25.96%
Maximum temperature reduction divided by the highest rooftop temperature (B/C)	31.21%	36.73%	27.98%	22.80%
Heat amplitude reduction	83.32%	82.58%	79.78%	74.88%

perature, 47.65%), followed by the shrub (*Aglaia odorata Lour.*; 12.57 °C; 36.17%), vine (*Wisteria sinensis*; 11.55 °C; 34.66%; incomplete growth), and groundcover (*Cynodon L.C. Rich.*; 9.31 °C; 25.96%) green roofs (Table 10). The same results were obtained using the maximum temperature reduction divided by the highest rooftop temperature (Table 10), indicating that the extensive green roofs could reduce the cooling energy load and carbon dioxide emissions.

3.7. *Impacts of the environment on temperature reduction of the extensive green roof, with and without plants*

All estimations were conducted using SPSS (version 21). Table 11 presents the estimates and goodness-of-fit measures of 24 simple ordinary least-squares equations, which regress the temperature difference between the bottom temperature of the extensive green roofs and the temperature of the bare rooftop in terms of air temperature, relative humidity, or solar radiation, based on measurements from the experimental and control beds (12 equations for each bed). First, all 24 equations had an F-statistic p value of 0.000, indicating that all 24 models were statistically significant and had sufficient predictive power. Second, the adjusted R-squared values of the 24 equations ranged from 0.302 to 0.732, suggesting that air temperature, relative humidity, and solar radiation account for approximately 30%–73% of temperature reduction variability. Third, all 24 equations had a t-statistic p value of 0.000, suggesting that air temperature, relative humidity, and solar radiation significantly affected the temperature difference between the bottom temperature of the extensive green roofs and the temperature of the bare rooftop.

The four air temperature models for the extensive green roofs had positive coefficients (1.233 °C to 1.936 °C), signifying that air temperature and temperature reduction engendered by the extensive green roofs were positively related. The higher the air temperature, the higher the magnitude of temperature reduction engendered by the extensive green roofs; this result is consistent with those of previous studies [26,33]. Of the four extensive green roofs, the *Impatiens walleriana* green roof (1.936 °C) elicited the highest magnitude of temperature reduction of the bare rooftop, achieving an additional 1.936 °C reduction for a 1 °C increase in air temperature. Furthermore, the absolute coefficient values were constantly higher for the extensive green roof than for the corresponding bare soil roof, suggesting that the plants facilitated the temperature reduction engendered by the extensive green roofs. This reduction could be attributed to greater shading, shielding, and evapotranspiration effects of the plants under higher air temperature.

The four relative humidity models for the extensive green roofs had negative coefficients (-0.484 °C to −0.261 °C), indicating that relative humidity and the temperature reduction engendered by the extensive green roofs were negatively related. The lower the relative humidity, the higher the magnitude of temperature reduction engendered by the extensive green roofs; this result is consistent with those of previous studies [26,33]. Of the four extensive green roofs, the *Impatiens walleriana* green roof (−0.484 °C) elicited the highest magnitude of temperature reduction of the bare rooftop, achieving an additional 0.484 °C reduction for a 1% decrease in relative humidity. Furthermore, the absolute coefficient values were constantly higher for the extensive green roof than for the corresponding bare soil roof, suggesting that the plants facilitated the temperature reduction engendered by the extensive green roofs. This reduction could be attributed to greater evapotranspiration effects of the plants under lower relative humidity.

The four solar radiation models for the extensive green roofs had positive coefficients (0.007 °C to 0.015 °C), indicating that solar radiation and the temperature reduction engendered by the extensive green roofs were positively related. The higher the solar radiation, the higher the magnitude of temperature reduction engendered by the extensive green roof; this result is consistent with that of a previous study [28]. Of the four extensive green roofs, the *Impatiens walleriana* green roof (0.015 °C) elicited the highest

Table 11
Regression analysis results.

Plant material (Date)	*Aglaia odorata Lour.* (2013/5/20 ~ 5/26)	*Impatiens walleriana* (2013/5/28 ~ 6/03)	*Wisteria sinensis* (2013/6/9 ~ 6/15)	*Cynodon L.C. Rich.* (2013/6/21 ~ 6/27)
Extensive Green Roof				
Air temperature (X_1) (°C)	$Y = 1.233X_1 - 32.045$ ($R^2 = 0.684$, $R^2_{adj} = 0.683$ $F_{(1,354)} = 765.7$, $p = 0.000$)	$Y = 1.936X_1 - 57.159$ ($R^2 = 0.542$, $R^2_{adj} = 0.540$ $F_{(1,371)} = 438.4$, $p = 0.000$)	$Y = 1.513X_1 - 43.385$ ($R^2 = 0.733$, $R^2_{adj} = 0.732$ $F_{(1,331)} = 907.0$, $p = 0.000$)	$Y = 1.420X_1 - 42.795$ ($R^2 = 0.603$, $R^2_{adj} = 0.602$ $F_{(1,312)} = 473.6$, $p = 0.000$)
Relative humidity (X_2) (%)	$Y = -0.261X_2 + 23.936$ ($R^2 = 0.581$, $R^2_{adj} = 0.579$ $F_{(1,354)} = 489.9$, $p = 0.000$)	$Y = -0.484X_2 + 36.395$ ($R^2 = 0.446$, $R^2_{adj} = 0.444$ $F_{(1,371)} = 298.5$, $p = 0.000$)	$Y = -0.325X_2 + 27.081$ ($R^2 = 0.577$, $R^2_{adj} = 0.576$ $F_{(1,331)} = 452.3$, $p = 0.000$)	$Y = -0.318X_2 + 23.937$ ($R^2 = 0.358$, $R^2_{adj} = 0.356$ $F_{(1,312)} = 174.0$, $p = 0.000$)
Solar radiation (X_3) (W/m^2)	$Y = 0.012X_3 + 1.354$ ($R^2 = 0.590$, $R^2_{adj} = 0.589$ $F_{(1,354)} = 510.3$, $p = 0.000$)	$Y = 0.015X_3 + 1.704$ ($R^2 = 0.536$, $R^2_{adj} = 0.535$ $F_{(1,371)} = 428.5$, $p = 0.000$)	$Y = 0.012X_3 + 0.393$ ($R^2 = 0.562$, $R^2_{adj} = 0.561$ $F_{(1,331)} = 424.7$, $p = 0.000$)	$Y = 0.007X_3 + 2.217$ ($R^2 = 0.305$, $R^2_{adj} = 0.302$ $F_{(1,312)} = 136.6$, $p = 0.000$)
Bare Soil Roof				
Air temperature (X_1) (°C)	$Y = 1.125X_1 - 29.424$ ($R^2 = 0.580$, $R^2_{adj} = 0.579$ $F_{(1,354)} = 489.7$, $p = 0.000$)	$Y = 1.755X_1 - 52.219$ ($R^2 = 0.422$, $R^2_{adj} = 0.420$ $F_{(1,371)} = 270.3$, $p = 0.000$)	$Y = 1.489X_1 - 43.259$ ($R^2 = 0.700$, $R^2_{adj} = 0.699$ $F_{(1,331)} = 773.4$, $p = 0.000$)	$Y = 1.357X_1 - 41.393$ ($R^2 = 0.523$, $R^2_{adj} = 0.522$ $F_{(1,312)} = 342.7$, $p = 0.000$)
Relative humidity (X_2) (%)	$Y = -0.230X_2 + 21.074$ ($R^2 = 0.460$, $R^2_{adj} = 0.458$ $F_{(1,354)} = 301.1$, $p = 0.000$)	$Y = -0.429X_2 + 32.025$ ($R^2 = 0.331$, $R^2_{adj} = 0.329$ $F_{(1,371)} = 183.7$, $p = 0.000$)	$Y = -0.313X_2 + 25.629$ ($R^2 = 0.529$, $R^2_{adj} = 0.528$ $F_{(1,331)} = 372.1$, $p = 0.000$)	$Y = -0.307X_2 + 22.555$ ($R^2 = 0.317$, $R^2_{adj} = 0.315$ $F_{(1,312)} = 144.9$, $p = 0.000$)
Solar radiation (X_3) (W/m^2)	$Y = 0.012X_3 + 0.818$ ($R^2 = 0.566$, $R^2_{adj} = 0.565$ $F_{(1,354)} = 462.4$, $p = 0.000$)	$Y = 0.014X_3 + 0.731$ ($R^2 = 0.473$, $R^2_{adj} = 0.471$ $F_{(1,371)} = 332.7$, $p = 0.000$)	$Y = 0.012X_3 - 0.288$ ($R^2 = 0.570$, $R^2_{adj} = 0.569$ $F_{(1,331)} = 439.5$, $p = 0.000$)	$Y = 0.007X_3 + 1.414$ ($R^2 = 0.304$, $R^2_{adj} = 0.302$ $F_{(1,312)} = 136.2$, $p = 0.000$)

Note: Y denotes temperature reduction caused by the extensive green roofs or the bare soil roofs (°C); X_1 denotes air temperature (°C); X_2 denotes relative humidity (%); X_3 denotes solar radiation (W/m^2).

magnitude of temperature reduction of the bare rooftop, achieving an additional 0.015 °C reduction for a 100 W/m^2 increase in solar radiation.

The effects of relative humidity, solar radiation, and air temperature on temperature reduction of bare rooftop could be limited by the plant types selected for the extensive green roofs. The effects of these parameters on the temperature reduction of the bare rooftop engendered by the extensive green roofs were derived from the top 12 equations presented in Table 11 (Fig. 18). The *Aglaia odorata Lour.* green roof had a higher temperature reduction performance at an air temperature of <35.5 °C than the other green roofs [(Fig. 18(A)). Furthermore, at a relative humidity of 75%, the *Impatiens walleriana* and *Cynodon L.C. Rich.* green roofs could not provide any temperature-reduction effects. The *Wisteria sinensis*

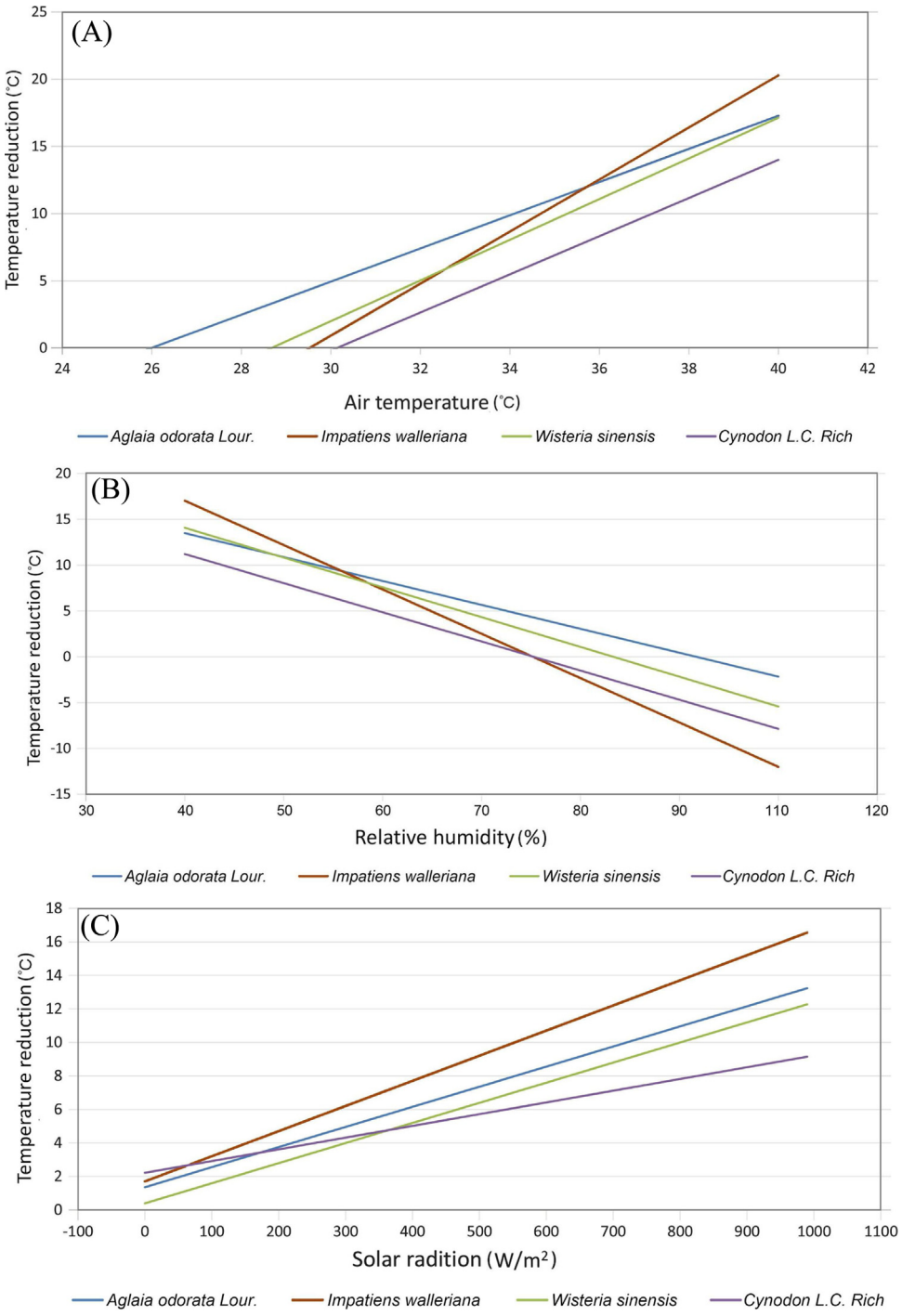

Fig. 18. The prediction of the effect of air temperature (A), relative humidity (B), and solar radiation (C) on temperature reduction of bare rooftop caused by the extensive green roofs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and *Aglaia odorata Lour.* green roofs could not exert temperature-reducing effects at a relative humidity of 84% and 92%, respectively [Fig. 18(B)]. In addition, the *Cynodon L.C. Rich.* green roof exhibited a higher temperature reduction performance under low solar radiation than the other green roofs. The *Impatiens walleriana* green roof had higher temperature reduction performance than the *Aglaia odorata Lour.*, *Wisteria sinensis*, and *Cynodon L.C. Rich.* green roofs under high solar radiation [Fig. 18(C)]. Therefore, it is suggested that the effects of the ambient environment be considered in selecting the type of plant for green roofs. Moreover, because the plant itself could establish a microclimate or canopy around the surrounding area, and the moisture in bare soil roof, the nearby bare soil roof had a trend in temperature reduction performance similar to that of the green roofs (Table 11).

4. Conclusions

Extensive green roofs have substantial thermal and energy benefits and provide a unique soothing and relaxing atmosphere for city occupants. We demonstrated that extensive green roofs constructed with one of four types of plants (groundcover, perennial herb, vine, and shrub) with healing potential (fragrance, distinct

flowers, or lush greenery) could elicit a temperature reduction relative to the bare rooftop (defined as the temperature of the bare rooftop minus the bottom temperature of the extensive green roofs) and heat amplitude reduction relative to the bare rooftop (defined as 1 minus the result of dividing the experimental temperature fluctuation by the rooftop temperature fluctuation). Our key conclusions are as follows:

1. Because of the reflective, photosynthetic, shielding, shading, and evapotranspiration effects of the vegetation layer and the insulation, absorption, and evaporation effects of the growth medium layer, in the relative terms, the perennial herb green roof (*Impatiens walleriana*) elicited the highest magnitude of temperature reduction of the bare rooftop, followed by the shrub (*Aglaia odorata Lour.*), vine (*Wisteria sinensis*), and groundcover (*Cynodon L.C. Rich.*) green roofs (Table 10).
2. For the aforementioned reasons, the shrub (*Aglaia odorata Lour.*) and perennial herb (*Impatiens walleriana*) green roofs elicited the highest magnitude of heat amplitude reduction of the bare rooftop (83.32% and 82.58%, respectively), followed by the vine (*Wisteria sinensis*, 79.78%; incomplete growth) and groundcover (*Cynodon L.C. Rich.*, 74.88%) green roofs (Table 11). Such reductions in heat amplitude relative to the bare rooftop are very desirable and beneficial for developing a comfortable and stable dwelling environment.
3. Vegetation resulted in an additional 3.98 °C (maximum) temperature reduction and an additional 16.45% (maximum) heat amplitude reduction compared with the bare soil roof.
4. Air temperature and solar radiation were positively related to temperature reduction of the bare rooftop; however, relative humidity was negatively related with.

Because of a limited experimental period, *Wisteria sinensis*, did not achieve full growth. We believe that additional thermal benefits could have been achieved if *Wisteria sinensis* had reached its optimal growth.

In the future, we suggest that to compare temperature reduction and heat amplitude reduction of a bare rooftop in absolute terms, first, four planting beds should be arranged simultaneously to better control the ambient environment. Second, given that most of the temperature reduction of the bare rooftop was attributed to the growth medium layer rather than the vegetation layer, further research could explore other types of growth medium with more air pockets or a higher energy absorption capacity, for example, to further lower the bottom temperature of the extensive green roof and to reduce the weight load on the building.

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